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PHYSICAL MODELLING AND TESTING OF AN ADVANCED GAS COOLED REACTOR CORE MODEL

O. Oddbjornsson⁽¹⁾, P. Kloukinas⁽¹⁾, L. Dihoru⁽¹⁾, M.Dietz⁽¹⁾, T.Horseman⁽¹⁾, E. Voyagaki⁽¹⁾, A.J. Crewe⁽¹⁾,
C.A. Taylor⁽¹⁾, A.G. Steer⁽²⁾

⁽¹⁾ University of Bristol, University Walk, BS8 1TR, Bristol, United Kingdom, A.J.Crewe@bristol.ac.uk

⁽²⁾ Engineer, EDF Energy Generation, Barnett Way, Barnwood, Gloucester, GL4 3RS, United Kingdom, alan.steer@edf-energy.com

Abstract

Advanced Gas Cooled Reactor (AGR) cores are multi-layered arrays of graphite components whose geometry and mechanical properties change under prolonged exposure to neutron irradiation. The presence of cracked components in the arrays later in their operational life may cause disruption of core geometry with implications for fuel cooling and control rod insertion in the event of a severe, but infrequent, seismic event. These ageing issues need addressing in both the computational and the physical models employed in the seismic resilience assessments. This paper presents a physical model with quarter-sized components of an array representative of those in AGR cores. The model was developed by the University of Bristol to provide experimental validation to computational tools which model high levels of core degradation. This paper outlines the principles of model design and the relevant aspects of rig development. The rig is tested on an earthquake simulator with the purpose to explore the mechanical interactions inside the array and to output acceleration and displacement data at selected locations. Relevant experimental outputs are presented showing dynamic responses of the array columns and top layer response maps. Overall, the model rig is capable of providing experimental evidence for the computational modelling methods, and so makes significant contributions to reducing uncertainties in these methods.

Keywords: reactor core; physical modelling; seismic resilience



1. Introduction

The Advanced Gas Cooled Reactors (AGR) are the second generation of British gas-cooled nuclear reactors, using graphite as the neutron moderator and carbon dioxide as the coolant. At the hearts of the AGRs are the cores which consist of arrays of graphite bricks arranged in columns and connected radially via a system of graphite keys within keyways cut into the graphite bricks. During normal operation, the graphite components are exposed to high levels of fast neutron irradiation and γ -rays that induce changes in the physical properties of the graphite, and generate stresses, deformations and weight loss. These changes have consequences for the operation of the reactors, the structural integrity of their permanent graphite and steel components and the reliability and effectiveness of their safety systems.

The fundamental nuclear safety requirements of the AGR cores are to allow unimpeded movement of control rods and fuel, and to secure adequate cooling of the fuel and core structure, both in normal and fault/hazard conditions. With regards to the seismic hazard, the current international standards require that a nuclear plant should be qualified against at least 0.1g peak ground acceleration, while the operators require that their nuclear power stations (AGRs) can be safely shut down and held down in the case of a more severe seismic event with a probability of exceedance of 10^{-4} per annum. This seismic capability needs to be demonstrated throughout the stations' lives and to take account of the consequences of fast neutron irradiation and radiolytic oxidation for graphite component behaviour. These degradation processes, which include changes in geometry, strength and the possibility of differential shrinkage induced cracking, need to be captured in the numerical reactor core models used to assess seismic capability and, where practicable, in the physical array models.

Currently, the seismic responses of the AGR cores are calculated using the GCORE finite element (FE) model [1] and the SOLFEC [2] solid-body code. Both numerical tools can determine the displacements, velocities, stresses and forces which occur when individual bricks and keys collide or otherwise come into contact with each other under the influence of various loadings. It is recognized that the aforementioned computer models need to be validated experimentally for higher percentages of degraded components that are associated with the AGR cores late in their life cycle. There is also a requirement to enhance the understanding of core dynamics, especially where components may behave in ways not explicitly modelled by the computational analysis (e.g. post key disengagement behaviour). A suitably representative physical model was required for this purpose.

Since 2008, the University of Bristol (UOB) has conducted an extensive body of technical work that lead to the design and build of a quarter scale physical model of an AGR core, known as the Multi-Layer Array rig (the 'MLA rig') [3]. The MLA's unprecedented complexity is pushing the boundaries of design in instrumentation, data acquisition and data processing: its number of model components is greater than 44,000 and the number of measurement sensors is greater than 3,000. This paper describes the reasoning process underpinning the design, build and testing of the rig, together with relevant aspects of instrumentation. Several examples of rig outputs are given that demonstrate the rig capability in producing data relevant for the numerical modellers.

2. Rig Description

2.1 Overview

The AGR cores consist of thousands of graphite moderator bricks interconnected through a graphite keying system which acts to resist relative motion between bricks. The graphite components are stacked together in vertical columns that provide the channels for fuel assemblies, control rods and coolant flow (Fig.1). The core columns must remain vertical within tight tolerances so that the control rods and the fuel stringers have a secure and unimpeded travel in and out the channels. The vertical faces between neighbouring bricks are separated by gaps to allow for graphite expansion during reactor operation. The radial keying system allows free radial movement of the bricks during thermal expansion and contraction of the surrounding steel structures, and provides reaction forces to lateral movement once the clearances between the keys and the keyways have been taken up (Fig.2).

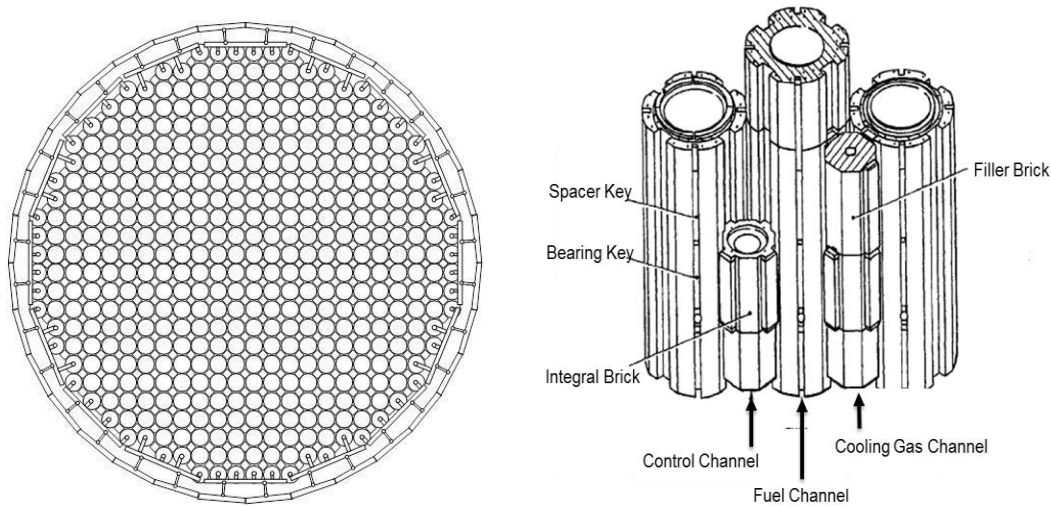


Fig. 1 - Plan view of AGR core and core restraint (left) and columns of bricks and keys (right).

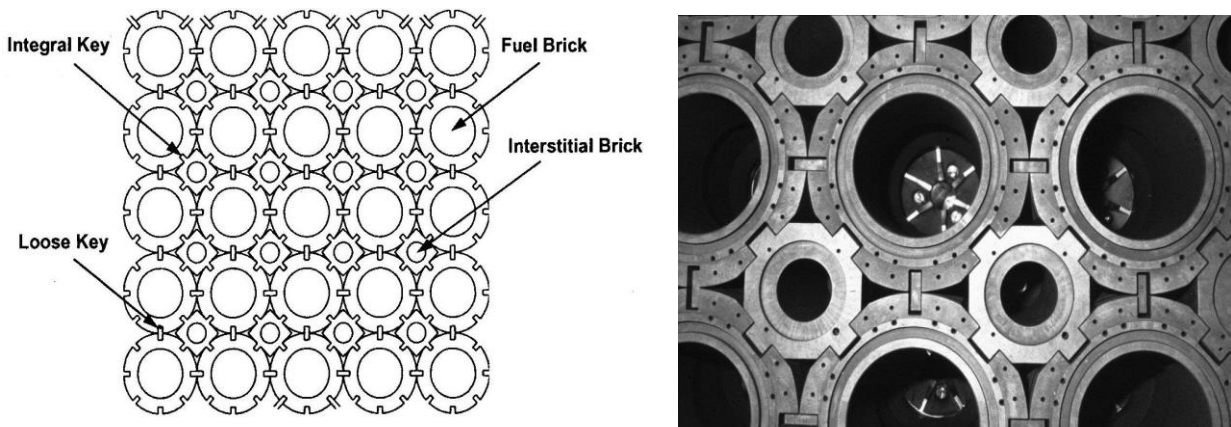


Fig. 2 - Layout of graphite core components in an AGR core showing the radial keying system.

For seismic loadings, the following areas of investigation are considered the most important for an AGR core:

- The effect of damage occurring before and during a seismic event, including keyway root cracking.
- The relative likelihood of the shape types that channels will distort into, for a given measure of freedom and vibration/seismic energy input.
- The effect on the control rod drop times
- The phenomenon of 'core tectonics', where islands/sections of contiguous functionality and functional failure form.

The inclusion of all the aforementioned aspects in a unique physical model would be highly challenging and excessively costly. Therefore, the UOB approach has been to concentrate on the effects of seismic loading on an already 'damaged' array (i.e. including irradiation shrinkage and cracking of the graphite components). Consequently, non-structural components such as the fuel and control rods are not modelled and the complex restraint system simplified. The following aspects of damaged core behaviour have been identified as targets for experimental investigation:

- a) Shape distortion of control channels and fuel channels.
- b) Core distortion due to variation of horizontal direct clearance between bricks brought about by advanced shrinkage.
- c) Core distortion due to large percentage of singly and/or doubly axially cracked bricks.
- d) Core distortion due to displaced / locked / failed graphite keys.
- e) Core distortion from crack opening, even if adjacent keys are not damaged.

The MLA rig development took place in stages of work spanning over 5 years. Fig. 3 presents a summary of this phased approach. The theoretical modelling stage investigated the scaling laws that were relevant in model design and established what core components need modelling and what mechanical interactions are relevant for the prototype in its present age-degraded status. The design of the model rig received inputs from previous exploratory testing on small arrays conducted at UOB, as well as from GCORE simulation work.

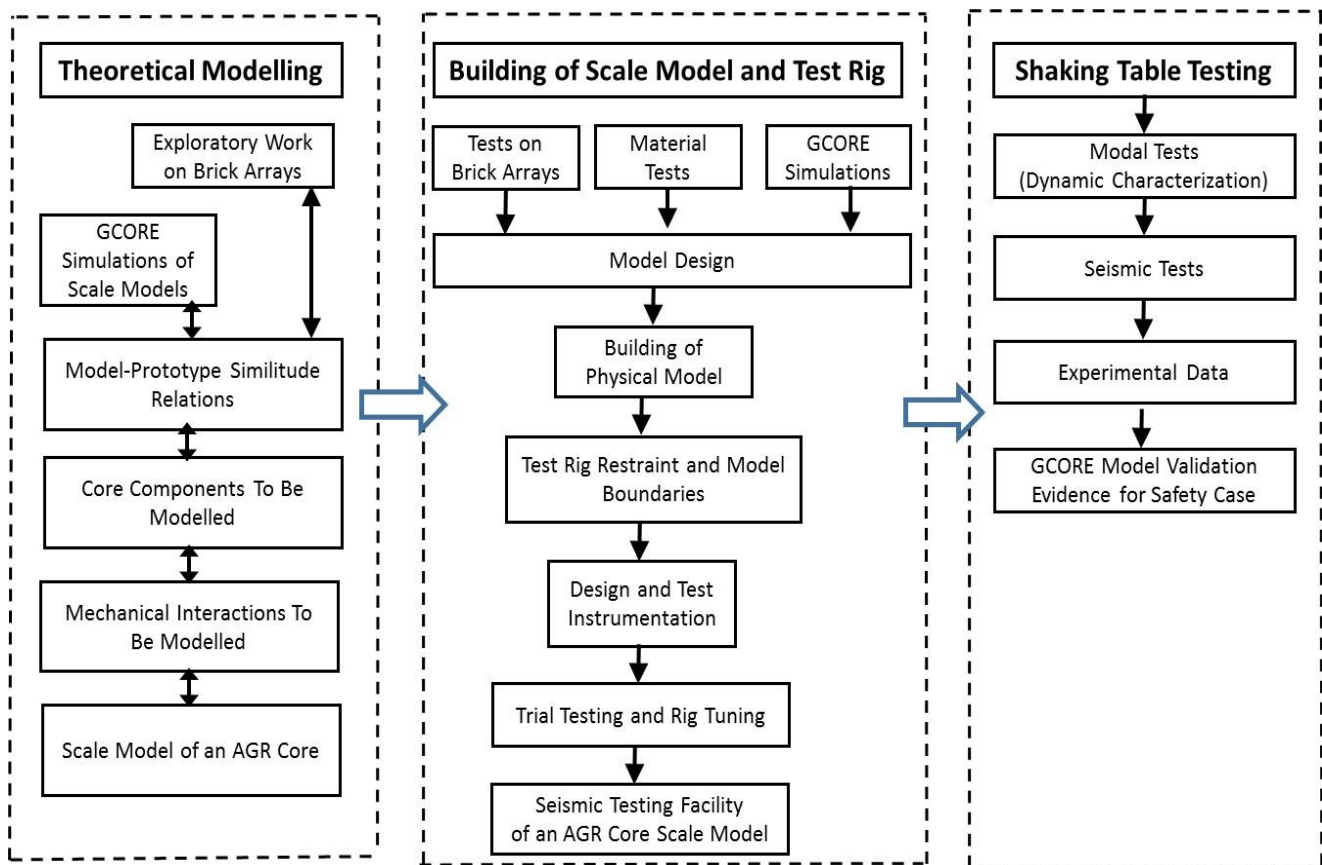


Fig. 3 - Overview of the MLA research programme

The rig feasibility study was complemented by dynamic testing work on two simpler physical models: a 4x4x8 array ('the Minicore') and a single layer 20-brick-across-array ('the Single Layer Array') [3] that contributed to component and instrument design verification (Fig. 4). The MLA physical model building and trialling work run in parallel with a collaborative programme of computer simulations of the scale model using GCORE. An iterative stage of trial testing and rig adaptation led to the successful commissioning of the MLA physical model in July 2014. Currently, the MLA work is in a production test stage and various array configurations are being tested extensively on the UOB's earthquake simulator. The experimental outcomes will serve as evidence to support AGR operations and as a validation tool for GCORE and any other capable computer modelling alternatives.

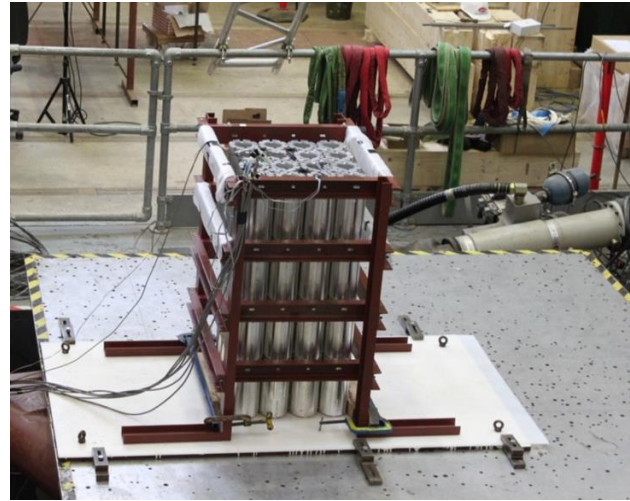
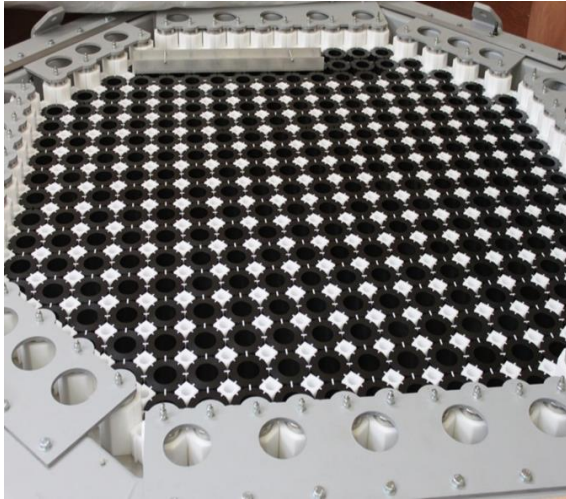


Fig. 4 – The single layer array rig (left) and the minicore (right)

2.2 Model design and considerations of dynamic behaviour

In general physical modelling seeks an adequate approximation of the similitude relations between model and prototype. In this particular case, the following basic prototype and model facts have been considered:

- a) A graphite density of 1.8 g/cm^3 has been historically assumed.
- b) An unirradiated graphite Young's modulus of 9.6 GPa has been assumed. The prototype Gilsocarbon graphite compressive strength is about 80 MPa.
- c) The point contact collisions between components are considered rigid.
- d) Geometrical similitude is required, including rocking features of model fuel bricks, parallel walls for keys and a dovetail shape for keyways.
- e) Dimensional precision is required (i.e. tolerance of 0.1 mm or smaller for linear dimensions).
- f) Key-keyway clearances are scaled for the correct reproduction of rotational and translational movements of the key in the keyway (prototype clearance: 1.04 - 1.52 mm).
- g) Mechanical properties of the model material should be stable with time, under normal environmental conditions.
- h) The ideal scaling factor for Young's modulus is 1. However, this poses severe restrictions on material properties and probably cannot be achieved in practice.
- i) The scaling factor for gravity is 1.
- j) The maximum dimension of model rig is dictated by the size of the shaking table platform (3m x 3m).
- k) The maximum weight of model rig is dictated by the capacity of the shaking table (15 tonnes).

A summary of scaling factors for earthquake response of structures can be found in [4]. In general, a true replica model implies simultaneous duplication of inertial, gravitational and restoring forces and full compliance with the similitude laws. Such a model would require scaling of density and stiffness at the same time. Finding a material whose properties satisfy scaling requirements simultaneously is practically impossible, therefore, an adequate approximation has to be sought. Another method employed in physical modelling is the artificial mass simulation method. It implies the presence of additional material of a non-structural nature to simulate the required density of the model. Such mass can be lumped or distributed. This method is difficult to apply to the scaled AGR core model because of the large number of components that have a role in system's dynamics. Distributing an artificial mass within such a complex array of rigid blocks would be technologically impractical. The third type of modelling applies to cases where gravity forces can be neglected. In the particular case of a graphite core under seismic loading, the gravitational forces cannot be neglected, therefore, using the third type of scaling law is out of the question. It was therefore proposed that the graphite core model should be an 'adequate model' which maintains 'first-order' similarity. 'First-order' similarity implies that the physical parameters with significant influence on the seismic response are accurately scaled, while the 'second-order'



parameters are only be approximately scaled. In this way a modified version of a true replica model will be created. For this research programme it was proposed that the geometrical properties of the core would be scaled, as the channel shapes and the general distortion of the core are governed by the brick-to-brick and the key-keyway clearances. It has been decided that the brick and key design will be a quarter scale design based on that of the most irradiated cores. All the clearances in the model are quarter scaled and determined from those predicted late in their lives. The scaling of material properties has also to consider the dynamic problem that is at the centre of the investigation. During a seismic event, the core will behave as an array of rigid bodies in which the relevant forces are the impact forces generated during the collisions between the components, the gravitational and the restoring forces. As impact forces depend on the local contact properties (i.e. contact stiffness and coefficient of restitution), then the Young's modulus of the component material becomes relevant in scaling. It is important to observe, that the contact properties are different for the normal and for the shear contact. The energy restitution after a brick-to-brick collision depends heavily on the actual layout of components in a zone of investigation (i.e. presence or absence of bearing key, presence or absence of integer key, locking of key, etc). Brick-to-brick testing of model components have been carried out to determine the values of contact properties for various component combinations.

The complexity of the physical model is generally determined by its number of components and level of precision in reproducing the geometry and scaled dimensions. The more complex the scale model, the higher its level of representation for the dynamic behaviour of a 'generic' prototype. The simpler the physical model, the more sophisticated the mapping software that extrapolates the experimental results should be for a realistic prediction of the prototype response. The smaller and stiffer the array, the smaller the relative displacements between the components, making measurement more challenging. Previous measurements in small array tests [5] show that the displacements in a 10x10x1 section are ~10mm maximum for the 100% cracked core, but only ~5mm for the 50% cracked core, and as small as ~1mm for the intact core. It is also important to note, that smaller and stiffer models are likely to respond at higher frequencies and that such behaviour would be a departure from the actual prototype for which a 'natural frequency' of 2-3Hz has been predicted. Lowering the 'natural frequency' of the model can be done via increased slackness in the system. As the horizontal clearance value should be representative of late life operations (i.e. it has a well-defined scaled value), then slackness can be increased via increased key-keyway clearances and/or via increased area section of the model. If the key-keyway clearances are to be kept quarter-scale of the prototype value, then the only route for increasing slackness is via a larger model section. This has led to the decision to design and build a near-full size, multi-layered array rig (MLA) with the following characteristics: quarter scale, octagonal shape, 20 bricks across the horizontal cardinal dimension representing the inner-most 10 rings of the AGR core, and 8 layers. To establish limits in behaviour, the MLA rig is designed to generate brick displacements of sufficient amplitude to exceed the current seismic assessment limits when simulating the effects of component degradation (i.e. doubly cracked bricks) and the increased brick-to-brick clearances arising from irradiation shrinkage in the AGR cores. The 16mm brick-to-brick gaps in the AGR prototype are scaled to 4mm in the MLA model.

The selection of the model material had to seek a reasonable approximation for the ratio between the scaling factor for density (S_ρ) and the scaling factor for stiffness (S_E) of the model component. This ratio is described by the basic scaling law in Eq. (1):

$$S_\rho = S_E / S_L \quad (1)$$

where S_L is the scaling factor for length. For a quarter scale model, Eq. (1) becomes:

$$S_\rho = 4 \times S_E \quad (2)$$

Table 1 presents the results of Eq. (2) for a number of candidate materials.

Table 1 - Scaling factors for density and stiffness for candidate model materials

Material	Density (kg/m ³)	Young's Modulus (GPa)	Compressive Strength (MPa)	S _p	S _E	S _p / S _E
Commercial Graphite	1800	9.60	70	1.00	1.00	1.00
Nylon 12	1020	1.80	75	0.57	0.19	3.02
POM	1410	2.70	90	0.78	0.28	2.79
Reinforced POM	1580	9.00	100	0.88	0.94	0.94
PPS(Fortron)	1600	13.00	93	0.89	1.35	0.66
LCP(Vectra)	1610	13.00	90	0.89	1.35	0.66
Aluminium Alloy	2700	70.00	110	1.50	7.29	0.21

Note: Property values are indicative. POM is the DIN abbreviation for polyoxymethylene. PPS (Fortron®) is polyphenylene sulphate with 40% glass reinforcement. LCP(Vectra®) is a liquid crystal polymer with 30% glass reinforcement (supplier: Ticona Ltd).



Fig. 5 - Quarter scale Acetal components in the MLA rig (left: columns, right: top layer)

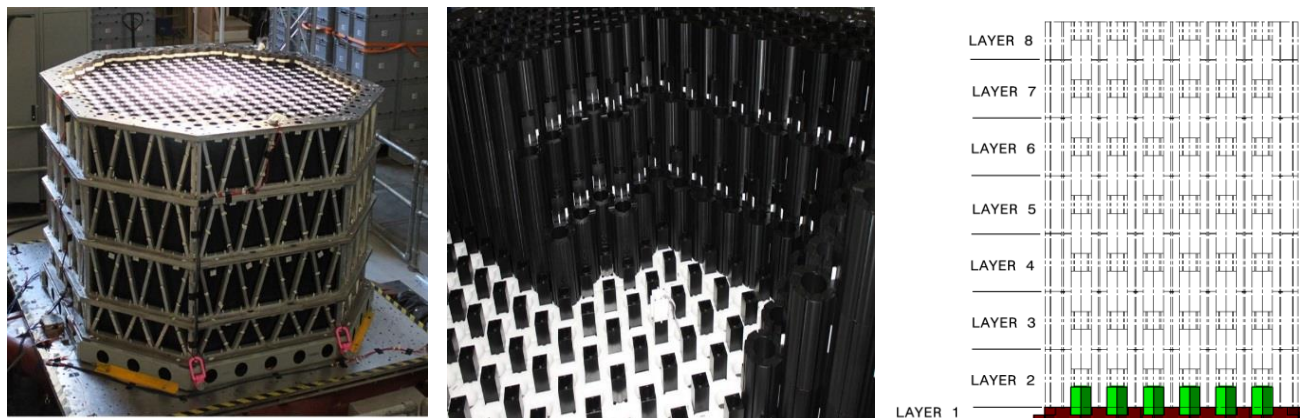


Fig. 6 - The ML restraint (left). Layer layout in the MLA rig (middle and right). Layer 1 is an assembly of plastic plates. Layers 2-8 are active.



The material selected for the model components is the engineering thermoplastic material called polyoxymethylene (DIN-abbreviated POM), commercially available as Acetal. Acetal exhibits a reasonable density/stiffness ratio and high rigidity which makes it suitable for precision machining. Also, Acetal is catalogued as non-hygroscopic, therefore the component dimensional tolerances are likely to be stable with time in normal environmental conditions. In addition, Acetal exhibits comparable friction characteristics to graphite (friction coefficient ~ 0.2).

The model components and their layout in the array are shown in Fig. 5. The base of the rig (Layer 1) (Fig. 6) is a seating assembly of plastic plates in which the array columns are socketed. The base secures the exact spacing between the bricks and allows radial rocking. Other grid bases may be used in the future, to emulate alternative horizontal direct clearances between bricks.

Because the experiment was intended to study the dynamic behaviour of the array, the actual complex core restraint assemblies were not represented. The boundary frame was designed to be dynamically rigid within the seismic test range (its natural frequency is above 35Hz). The lateral boundary restraint arrangements provide the required rigidity of the perimeter model bricks, while allowing for sufficient adjustment to accommodate alternative brick pitches. The restraint base frame is rigid and allows for precise levelling of the base plastic plate assembly on which the model bricks are founded. More details on rig development and operation can be found in [6, 7].

2.3 Instrumentation

A summary of the physical parameters that are measured in the rig and the instrumentation employed for this purpose is given in Table 2.

Table 2- Instruments and measurands in MLA rig testing

Instrument/ Measurement System	Measurands
Infrared Vision System (IRVS)	Displacement of array components, ML restraint frame, shaking table
High Speed Video System (HSVS)	Displacement of array components in top layer
Accelerometers (SETRA type)	Acceleration of shaking table and ML restraint frame
Accelerometers (MEMS* type)	Acceleration of interstitial/filler/lattice bricks
Hall Effect Sensors	Interstitial channel profile, loose bearing key position in the keyway, doubly cracked brick monitoring
Linear Potentiometric Transducers	Lattice channel profile

Note: MEMS* stands for Micro-Electro-Mechanical-System

The lattice channel measurements are obtained with potentiometric transducers installed on the bottom face of each model lattice brick in the instrumented column (Fig. 7.1). Each filler and integrally keyed brick in the instrumented interstitial columns is equipped with a 3-axis accelerometer, while each lattice brick in the instrumented lattice columns contains 2 off 3-axis accelerometers (at the top and bottom). The interstitial channel profiles are measured using Hall effect sensors mounted on both the top and bottom faces of each filler brick (Fig. 7.2) in the instrumented column. Sets of three magnets are embedded in the vertically adjacent integrally keyed bricks (Figure 7.3) to interact with the Hall effect sensors in the filler bricks. These produce sensor voltages that can be converted into 6 DOF (degrees of freedom) of the filler-to-interstitial brick interface. The channel sensor outputs are acquired by a novel distributed micro data acquisition system (microDAQ) system consisting of a large number of 16/32-channel DAQ systems hosted by the instrumented filler and the

instrumented lattice bricks. The brick interface measurements are integrated up the columns to generate channel profiles. The MLA array also contains a pattern of infrared markers rigidly attached to selected components in the top layer that can be tracked by an infrared camera system. Figure 7.4 shows an example of 3 infrared markers (A, B and C) attached to a lattice brick in the top layer.

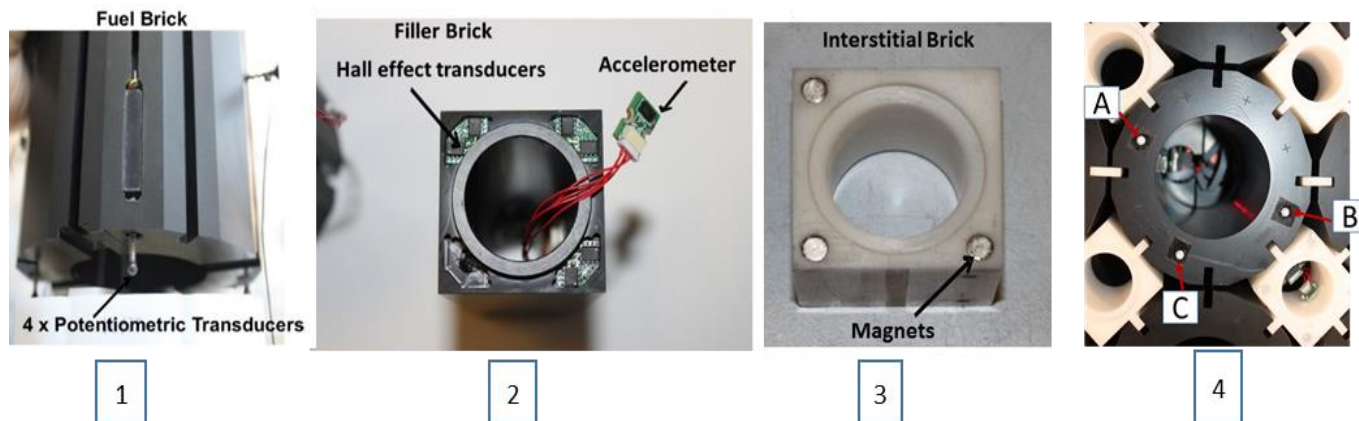


Fig. 7 - Instruments in the MLA - 1: instrumented lattice brick, 2: instrumented filler brick, 3: instrumented interstitial brick, 4: lattice brick with infrared markers (A, B and C).

3. Examples of Experimental Outputs

The MLA programme of testing is driven by the computer modeller needs, being designed to generate results for comparison against primary GCORE model outputs such as brick-to-brick displacements and channel profiles. The main objectives are to reduce the uncertainties in the numerical tool, to investigate the interactions between keys and keyways before and after disengagement and to investigate how far the current assessment limits are from cliff-edge behaviour. The focus of testing is on scaled input motions that are derived from the hazard inputs and resulting responses predicted as part of the seismic assessments of the UK's AGR stations. The seismic inputs are applied as directional rosettes with 22.5° or 45° increments, at acceleration magnitudes varying from 0.05g to 1g. A summary of typical inputs employed in testing is presented in Table 3.

Table 3 - Typical inputs employed in MLA testing

Input Type	Input Characteristics	Input Direction	Comments
White noise	Frequency range: 0-100Hz Acceleration amplitude (RMS*): 0.04g	X, Y, Z	Modal testing for MLA restraint with and w/o array. Explore resonant frequencies. Investigate symmetry of restraint.
Sinusoidal dwell	Frequency: 1Hz, 2Hz, 3Hz, 4Hz, 5Hz Acceleration amplitude (pk-pk*): 0.1g, 0.3g, 0.5g, 0.8g	X, Y	Explore frequency response and ability to replicate basic mechanics.
Seismic	Time history generated from secondary response spectra at AGR power stations, 10e-4 probability of occurrence. Time scaled (time scaling factor*=2)	rosette	Explore onset of changes of behaviour. Amplification of response for certain frequencies and energy bands.
Seismic	Time history generated from secondary response spectra at AGR power stations, 10e-4 probability of occurrence. Unscaled	rosette	Effect of input scaling on response.

*RMS: Root Mean Square (quadratic mean of acceleration); *pk-pk: peak to peak; *time scaling factor of 2 derived from length scaling factor of 4.

Fig. 8 and Fig. 9 summarize the response of the experimental array to the Hinkley Point B (HPB) input motion, see Fig. 10, which is a calculated secondary response at the base of the core. Hinkley Point B is one of the seven AGR core power stations in the UK. The tests presented were conducted in the X direction, at four levels of gain, i.e. 20%, 60%, 100% and 140%. Fig. 8 shows the displacements of the lattice bricks in the top layer of the array (layer 8) relative to the restraint frame. The contours of maximum relative displacement are shown for the aforementioned four levels of input gain. The response appears to be largely symmetrical, with the maximum relative displacements recorded in the central part of the array. Under dynamic excitation, the array behaves like a system of rigid bodies in which the relevant forces are the impact, the inertial and the gravity forces. The energy restitution after a brick-to-brick collision depends heavily on the actual layout of components in a region of investigation (i.e. component-to-component gap, presence or absence of bearing key, presence or absence of interstitial key, locking of key, etc). In general, the array behaviour is displacement driven, being governed by the brick-to-brick and the key-keyway clearances. The relative movements of the bricks in the central region of the array move more due to gap accumulation effects than the bricks at the periphery whose movements are restricted by the presence of the frame boundary.

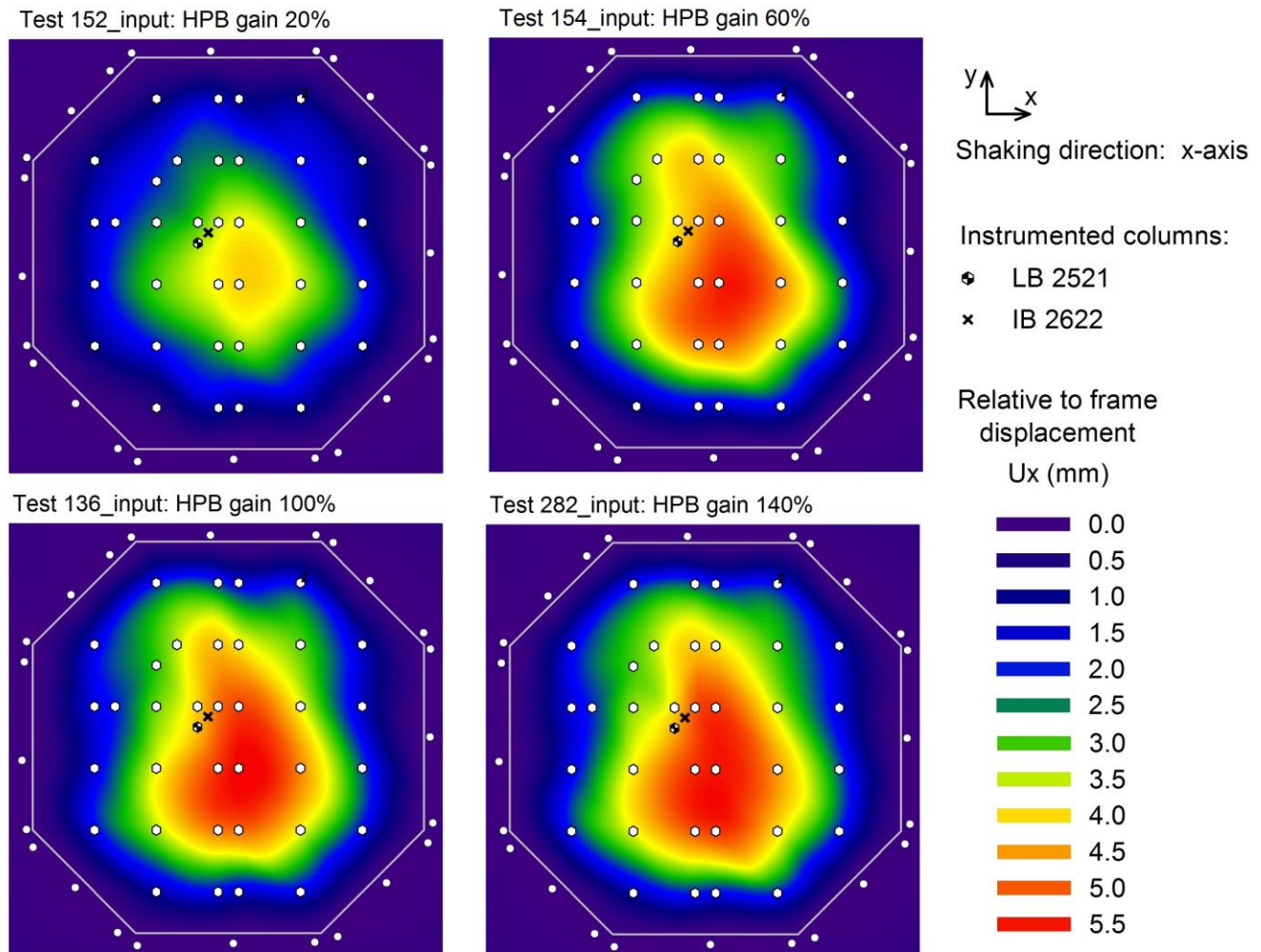


Fig. 8 – Contours of maximum relative displacement for the lattice bricks in the top layer, for HPB seismic input at four levels of input gain.

Fig. 9 presents, for the same tests as before, the maximum deflection envelope for one representative lattice column (i.e. LC2521) and one representative interstitial column (IC2622). An interstitial column in the experimental rig consists of a stack of 14 components, a fixed hybrid filler brick at the bottom with 7 interstitial bricks above spaced out by filler bricks. Horizontal movements of the 13 filler to interstitial brick interfaces are restricted by spigots allowing small horizontal translations and unrestricted rotations at the joint. A lattice column in the experimental rig consists of a stack of 7 components, 6 lattice bricks and one shorter hybrid lattice brick at the top of the stack. Horizontal movements at the lattice to lattice brick interfaces are eliminated by keying the two bricks together while still allowing rotations. For both types of columns, the channel profiles show increasing levels of deflection as the input acceleration increases. The columns behave largely like beams restricted at the bottom, with maximum deflection recorded at or towards the top of the array.

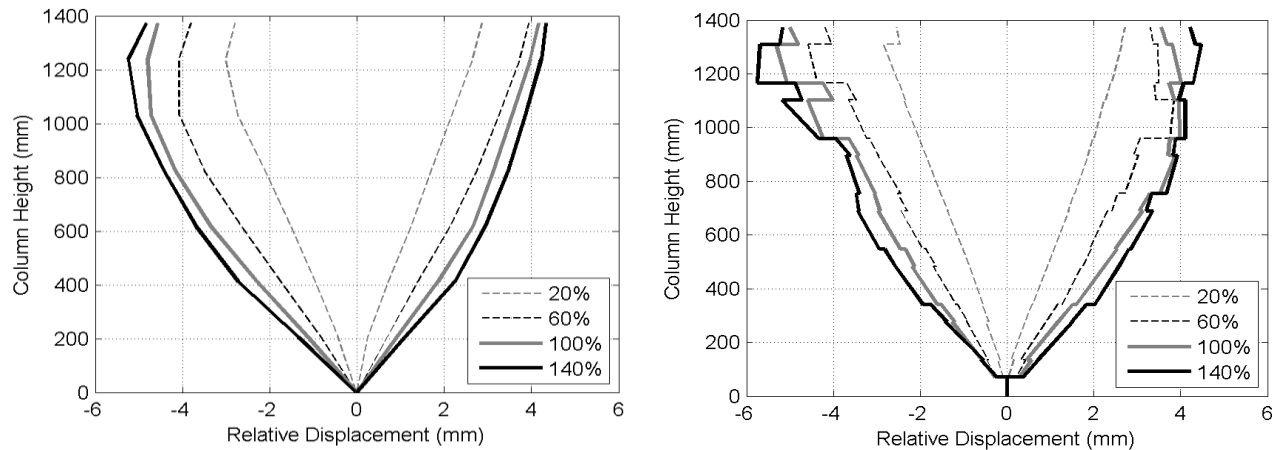


Fig. 9 – Maximum deflection envelope for instrumented lattice column LC2521 (left) and instrumented interstitial column IC2622 (right), for HPB seismic input at four levels of input gain.

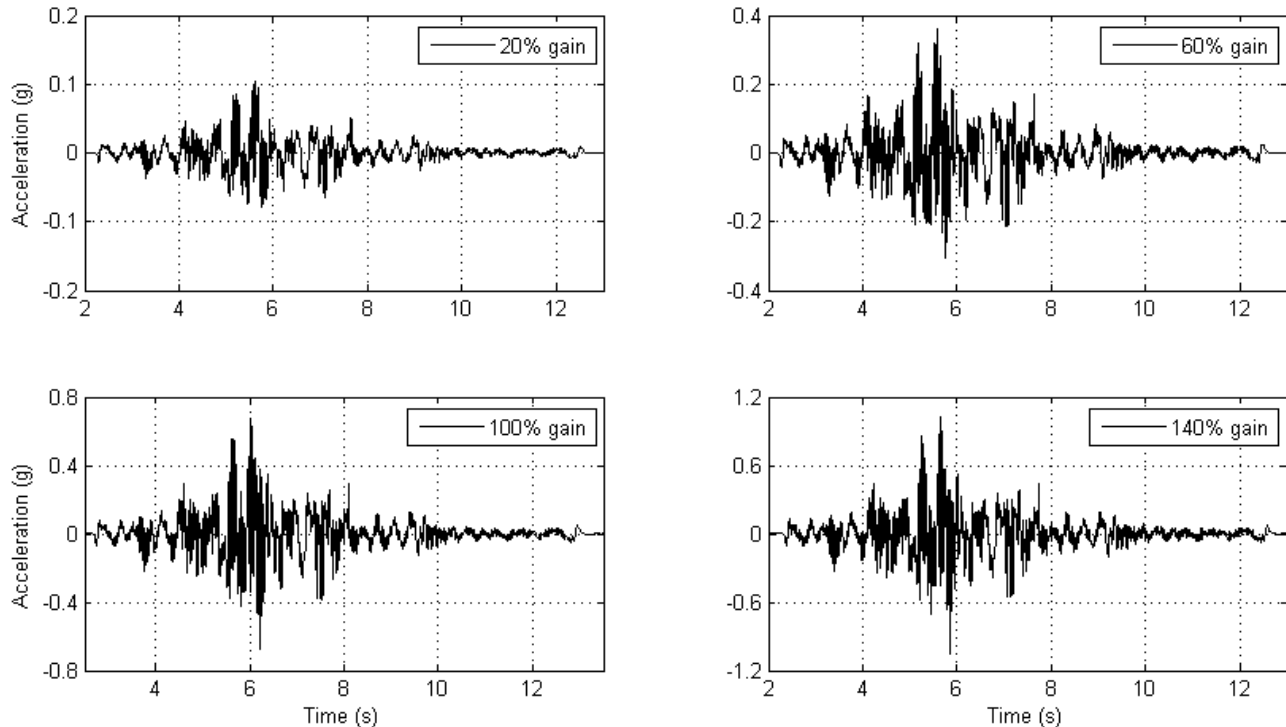


Fig. 10 – The HPB seismic input motion at the four relevant gain levels, 20% at top-left, 60% at top-right, 100% at bottom-left and 140% at bottom-right.



4. Conclusions

A highly complex quarter scale physical model representative of the keyed arrays of bricks used in AGR graphite cores has been presented. The decision making process that underpinned the rig design and build, which included investigations of model scaling, material selection and instrumentation design, has been described. The rig provides displacement and acceleration data for the array components, as well as channel profile measurements. Several examples of rig outputs are given that demonstrate the rig capability of exploring the mechanics inside the array for a variety of dynamic inputs. The goal of the MLA experimental programme is to provide evidence for validation of the existing numerical seismic models and to quantify their validity limits.

5. Acknowledgement

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